DEVELOPMENT OF AEROBIC GRANULAR SLUDGE TECHNOLOGY FOR DOMESTIC WASTEWATER TREATMENT IN HOT CLIMATES

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To Dania, Aklam and my parents

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ABSTRACT

Conventional domestic wastewater treatment plants based on activated sludge technology require large footprint (big settling tank) due to the relatively slow settling characteristics of sludge flocs. Aerobic Granular Sludge (AGS) technology offers a possibility to design a compact system based on simultaneous organic and nutrient removal and because of the good settling characteristics of the AGS, the use of a big settling tank is not necessary. Therefore, the installation can be more compact, at a cheaper cost. The aim of this study was to develop AGS system for domestic wastewater treatment applications in hot climate conditions. Special emphasis is given to the settling characteristics and physical strength of the AGS. Therefore, a 3-litre laboratory-scale reactor known as Cyclic Aerobic Granular Sludge Bioreactor (CAgSBio) was designed and used. The operation of the reactor was based on the Sequencing Batch Reactor (SBR) system with a complete cycle operation of three (3) hours and specifically designed to be operated for twenty-four (24) hours continuously at temperature of 30ºC. A 3-litre laboratory-scale reactor in Delft University of Technology (TU Delft), the Netherlands operated at 20ºC was also used to compare the results on AGS granulation and performance. AGS developed at this low temperature and from a 1.4 m^3-pilot plant at Ede Wastewater Treatment Plant, the Netherlands (fed with pre-treated domestic wastewater) were also used for a physical strength study, to compare with AGS at 30ºC. All analytical measurements performed in this study were conducted according to *Standard Methods for the Examination of Water and Wastewater* (APHA, 2005). The study shows that after ninety (90) days of operation, stable AGS (fed with synthetic wastewater) with average size of 1.1 mm were formed at 30ºC. To demonstrate the simultaneous organic and nutrient removal by AGS, a removal study was also conducted. CAgSBio system showed stable removal performance. Average removal efficiencies during steady state cycles at 30ºC of organic carbon, total inorganic nitrogen and phosphorus reached 100%, 94% and almost 98% respectively. A study with actual wastewater (pre-treated domestic wastewater) at 30ºC indicates that the granulation process does occur but at a slower rate (125 days is essential to develop mature granules) compared to synthetic influent (90 days). Meanwhile, AGS settling behaviour study shows that AGS settled relatively fast (velocities >12 mh^{-1} for size > 0.2 mm) compared to other conventional sludge flocs. The study also indicates that excessive mixing is not favourable for AGS reactors. Thus, the mixing criteria for AGS reactors was developed based on results obtained through experiments under mechanical and aerated-mixing conditions. Finally, a procedure was developed to evaluate the AGS strength based on the stability of AGS against shear stress. Determination of a stability coefficient (*S*) was introduced as an indicator of AGS strength. The results shows that AGS at 20ºC and 30ºC, fed with synthetic wastewater are very stable. For AGS fed with pre-treated domestic wastewater, the AGS at 30ºC (produced using the laboratory-scale reactor) is more stable than the AGS at 20ºC (produced using the pilot plant). As a conclusion, stable and compact AGS can be developed and performed effectively in hot climate conditions for domestic wastewater treatment applications, particularly as an alternative technology which is compact, high speed operation process (≈3 hours complete cycle) and more efficient.

ABSTRAK

Loji rawatan air sisa domestik konvensional yang berasaskan kepada teknologi enapcemar teraktif memerlukan keluasan tapak yang besar (tangki enapan besar) disebabkan oleh cirri enapan flok enapcemar yang secara relatifnya perlahan. Teknologi Enapcemar Granular Aerobik (AGS) menawarkan kemungkinan untuk mereka bentuk sistem kompak berdasarkan kepada penyingkiran organik dan nutrien serentak dan disebabkan oleh ciri enapan AGS yang baik, penggunaan tangki enapan yang besar tidak diperlukan. Oleh itu, pemasangan boleh lebih kompak, pada kos yang murah. Matlamat kajian ini adalah mengbangunkan sistem AGS untuk aplikasi rawatan air sisa domestik pada keadaan iklim panas. Penekanan khas diberikan kepada ciri enapan dan kekuatan fizikal AGS. Oleh itu, reaktor berskala makmal-3 liter dikenali sebagai Bioreaktor Enapcemar Granular Aerobik Berkitar (CAgSBio) telah direka bentuk dan digunakan. Pengendalian reaktor adalah berdasarkan kepada sistem Reaktor Kelompok Berjujukan (SBR) dengan pengendalian kitaran lengkap tiga (3) jam dan direka bentuk khas supaya boleh dikendalikan untuk dua puluh empat (24) jam secara berterusan pada suhu 30^{o}C. Reaktor berskala-makmal-3 liter di Universiti Teknologi Delft (TU Delft), Netherlands yang dikendalikan pada 20^{o}C juga telah digunakan bagi perbandingan keputusan granulasi dan prestasi AGS. AGS yang telah dihasilkan pada suhu yang rendah ini dan AGS dari Loji Pandu-1.4 m^3 di Loji Rawatan Air Sisa Ede, Netherlands (suapan dengan air sisa domestik pra-rawatan) juga telah digunakan untuk kajian kekuatan fizikal, bagi perbandingan dengan AGS pada 30^{o}C. Semua pengukuran analitikal dalam kajian ini telah dikendalikan mengikut *Kaedah Piawaian bagi Penilaian Air dan Air Sisa* (APHA, 2005). Kajian ini menunjukkan bahawa selepas sembilan puluh (90) hari pengendalian, AGS yang stabil (suapan dengan air sisa sintetik) dengan saiz purata 1.1 mm telah terbentuk pada 30^{o}C. Untuk menunjukkan penyingkiran organik dan nutrien serentak oleh AGS, kajian penyingkiran juga telah dibuat. Sistem CAgSBio telah menunjukkan prestasi penyingkiran yang stabil. Kecekapan penyingkiran purata organik karbon, nitrogen tak organik dan fosforus semasa kitaran keadaan mantap pada 30^{o}C mencapai 100%, 94% dan hampir 98%. Kajian dengan air sisa sebenar (air sisa domestik pra-rawatan) pada 30^{o}C pula menunjukkan bahawa proses granulasi berlaku tetapi pada kadar perlahan (125 hari diperlukan untuk menghasilkan granular yang matang) berbanding dengan influen sintetik (90 hari). Sementara itu, kajian kelakuan enapan AGS menunjukkan bahawa AGS terenap secara relatifnya cepat (halaju > 12 mh^{-1} untuk saiz > 0.2 mm). Kajian juga menunjukkan bahawa pembauran yang berlebihan tidak sesuai bagi reaktor AGS. Dengan itu, kriteria pembauran untuk reaktor AGS telah dibangunkan berdasarkan kepada keputusan yang telah diperolehi melalui eksperimen pada keadaan pembauran-pengudaraan dan mekanikal. Akhir sekali, satu tatacara telah dihasilkan untuk menilai kekuatan AGS berdasarkan kepada kestabilan AGS melawan tegasan ricih. Penentuan pekali kestabilan (*S*) telah diperkenalkan sebagai penunjuk kekuatan AGS. Keputusan menunjukkan bahawa AGS pada 20^{o}C dan 30^{o}C, suapan dengan air sisa sintetik adalah sangat stabil. Bagi AGS suapan dengan air sisa domestik pra-rawatan, AGS pada 30^{o}C (telah dihasilkan denngan menggunakan reaktor berskala-makmal)adalah lebih stabil berbanding AGS pada 20^{o}C (telah dihasilkan dengan menggunakan loji pandu). Sebagai kesimpulan, AGS stabil dan padat boleh dihasilkan dan bertindak secara cekap untuk aplikasi rawatan air sisa domestik pada keadaan iklim panas, terutamanya sebagai teknologi alternatif yang mana kompak, proses pengendalian yang pantas (kitaran lengkap 3 jam) dan lebih cekap.

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LIST OF ABBREVIATIONS

AGS	-	Aerobic Granular Sludge
APHA	-	American Public Health Association
B_{AGS}-1	-	No. of Bacteria Strain
BAS	-	Biofilm Airlift Suspension
BFB	-	Biofilm Fluidized Bed
CAgSBio	-	Cyclic Aerobic Granular Sludge Bioreactor
Ca^{2+}	-	Calcium (II)
Cd^{2+}	-	Cadmium (II)
CH_3COO^--C	-	Acetate
CH_4	-	Methane
CO_2	-	Carbon Dioxide
CAS	-	Conventional Activated Sludge
COD	-	Chemical Oxygen Demand
CMTR	-	Completely Mixed Tank Reactor
DPAO	-	Denitrifying Phosphate Accumulating Organisms
DO	-	Dissolved Oxygen
EA	-	Extended Aeration
EBPR	-	Enhanced Biological Phosphorus Removal
EGSB	-	Expanded Granular Sludge Blanket
FISH	-	Fluorescence In Situ Hybridization
GAOs	-	Glycogen Accumulating Organisms
GSBR	-	Granular Sludge Batch Reactor
HCl	-	Acid Hydrochloric
H/D	-	Ratio of Reactor Height to Diameter
HRT	-	Hydraulic Retention Time

IC	-	Internal Circulation
KCl	-	Kalium Chloride
K_2HPO_4	-	Potassium Hydrogen Phosphate Anhydrous
KH_2PO_4	-	Potassium Dihydrogen Phosphate
MBR	-	Membrane Bioreactor
$MgSO_4.7H_2O$	-	Magnesium Sulfate Heptahydrate
MLSS	-	Mixed Liquor Suspended Solids
MLVSS	-	Mixed Liquor Volatile Suspended Solid
N/COD	-	Nitrogen and Organic Ratio
N_2	-	Nitrogen Gas
NaAc	-	Sodium Acetate
NaOH	-	Sodium Hydroxide
NH_4^+-N	-	Ammonium
NH_4Cl	-	Ammonium Chloride
NO_2^+-N	-	Nitrite
NO_3^+-N	-	Nitrate
OLR	-	Organic Loading Rate
P	-	Phosphorus
P/COD	-	Phosphorus and Organic Ratio
PAOs	-	Phosphate Accumulating Organisms
PHA	-	poly-a-hydroxyalkanoates
PHB	-	poly-b-hydroxybutyrates
PO_4^{-3}-P	-	Phosphate
SBR	-	Sequencing Batch Reactor
SND	-	Simultaneous Nitrification and Denitrification
SBAR	-	Sequencing Batch Airlift Reactor
SRT	-	Solids / Sludge Retention Time
STP	-	Sewage Treatment Plant
SVI	-	Sludge Volume Index
Total-N	-	Total Nitrogen
TUDelft	-	Delft University of Technology
TSS	-	Total Suspended Solids
UASB	-	Upflow Anaerobic Sludge Blanket
USB	-	Upflow Sludge Blanket

UTM	-	Universiti Teknologi Malaysia
VFA	-	Volatile Fatty Acid
WWTP	-	Wastewater Treatment Plant
Zn^{2+}	-	Zinc (II)

LIST OF SYMBOLS

D	-	Blade diameter
D/T_{v}	-	Ratio of blade and vessel diameter
K'	-	Turbulent diffusion coefficient
N	-	Stirrer speed
P_0	-	Standard pressure
P_T	-	Absolute pressure
p-value	-	Significance level
Q_{air}	-	Airflow rate
r	-	Bubbles size
r-value	-	Correlation coefficient
S	-	Stability coefficient
T	-	Temperature
T_{v}	-	Vessel diameter
X	-	Total dry weight of aerobic granular sludge
X'	-	Total dry weight of aerobic granular sludge residual
Σ	-	Percentage of change of AGS diameter
θ	-	Temperature coefficient
γ	-	Shear rate
ϕ	-	Diameter
ϕ_{AGS}	-	Diameter of aerobic granular sludge
ρ_{AGS}	-	Density of aerobic granular sludge
ν_{AGS}	-	Settling velocity of aerobic granular sludge
X_{max}	-	Maximum growth concentrations of cell

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Before World War II, only several municipal and industrial wastewater treatment plants were built, mainly consisting of mechanical separation and settling tanks. These treatment systems could be extended with anaerobic tanks for sludge stabilisation. The first generation of activated sludge systems was built in the 1920's, after the study on suspended growth treatment and the discovery of activated sludge by Arden and Lockett in 1914 (de Kreuk, 2006). A number of activated sludge processes and design configurations have evolved since its early conception as a result of : (1) engineering innovation in response to the need for high quality effluents; (2) technological advances in equipment and process control; (3) increased understanding of microbial processes and fundamentals; and (4) the continual need to reduce capital and operating costs for municipalities and industries. Other activated sludge processes that have been found in many applications, with their dates of major interest in parentheses, include the oxidation ditch (1950s), contact stabilisation (1950s), Krause process (1960s), pure oxygen activated sludge (1970s), Orbal process (1970s), deep shaft aeration (1970s) and sequencing batch reactor (SBR) process (1980s) (Metcalf and Eddy, 2003). The basic idea behind the system was to reduce the treatment of wastewater to a one-reactor system. Although, major problems of this system were filaments often developed and biomass effluent separation was poor (Irvine and Ketchum, 1989; Wilderer *et al.*, 2000; Badreddine, 2008). However, the SBR system did receive worldwide attention and several thousands SBR facilities have since been designed, built and put into operation (Wilderer *et al*., 2000, Hastings *et al.*, 2007). Most sewage treatment facilities are still based on the continuously-operated activated sludge processes.

In an activated sludge system, a mixed culture of suspended biomass is growing and removing organic carbon and nutrients from the influent. In such a process the biomass (the activated sludge), which are usually present as flocs, are mixed with the wastewater in a large aerated basin. Supply of fresh wastewater to the bioreactor and discharged of treated wastewater from the bioreactor occur continuously. The discharged wastewater is led to a settling tank. In the settler, separation of activated sludge from the treated wastewater is carried out by means of gravitational forces. The treated wastewater can then be discharged into surface waters, or is used for further treatment (Metcalf and Eddy, 2003). Conventional activated sludge plants produce surplus sludge. Part of the settled activated sludge is recycled to the bioreactor. The remainder of the sludge is usually treated anaerobically and later disposed in landfills, or is used as fertilizer in agriculture. Conventional activated sludge plants take up a substantial footprint. In order to treat large amounts of wastewater completely, large aeration tanks are needed. The settling tanks cover a large areas, because the settling velocity of the activated sludge flocs is very low, normally <1 mh^{-1} (Beun *et al*, 2001; Metcalf and Eddy, 2004; Katja and Mika, 2007). Since the available ground area to build the treatment plant is usually limited, especially in Malaysia, there is a need for a more compact and high performance reactor.

This need for more compact reactors and short hydraulic retention time (HRT) directed the study towards the development of systems with high biomass concentrations. The AGS technology was proven as an alternative technology for compact and high performance system to treat wastewaters (Morgenroth *et al*., 1997; Beun *et al*., 1999; Tay *et al.,* 2002; de Bruin *et al.,* 2004; Liu and Tay, 2004; de

Kreuk *et al*., 2005; Zitomer *et al*., 2007; Sunil *et al*., 2008). AGS technology offers a possibility for compact wastewater treatment plant based on simultaneous organic (Chemical Oxygen Demand, COD) and nutrient (Nitrogen and Phosphorus) removal in one sequencing batch reactor. Because of the high settling capacity of the granules, the use of a traditional settler is not necessary and therefore, the installation can be very compact and at a cheaper cost.

Most of the AGS studies carried out so far were at low temperature (between 8 and 15^{o}C) and room temperature (between 20 and 25^{o}C). As a result, it is not fully known how these systems respond to changes at high temperature. In Malaysia, the temperature of domestic sewage is usually around 30^{0}C. The formation and stability of AGS at this temperature have not been studied extensively up to this date.

1.2 Objectives of the Study

The overall aim of this study was to develop an AGS system with special emphasis on temperature effects, settling and physical characteristics for the enhancement of domestic wastewater treatment systems. This can be achieved by the following specific objectives:-

i. To develop AGS at 30^{o}C using Cyclic Aerobic Granular Sludge Bioreactor (CAgSBio) and to compare with AGS at 20^{o}C developed using Sequencing Batch Airlift Reactor (SBAR), TU Delft, and Granular Sludge Batch Reactor, Ede, the Netherlands.

ii. To investigate the performance of AGS to remove organic matter and nutrients simultaneously at 30^{o}C in CAgSBio system, and to identify microbial populations of AGS using molecular techniques (via 16S rDNA sequence analysis).

iii. To develop AGS in CAgSBio system using actual wastewater (pre-treated domestic wastewater).

iv. To study the settling behaviour of AGS and to develop mixing criteria for AGS reactors.

v. To study the physical strength of AGS and to develop procedures for evaluation of AGS physical strength based on determination of stability coefficient (*S*), in which *S* represents an indicator of AGS strength (stability of AGS against shear stress). AGS from different sources, (i.e. developed at 20 and 30^{o}C, fed with synthetic and pre-treated sewage from CAgSBio, SBAR and GSBR) were used as samples to establish *S* values.

1.3 Scope of the Study

A 3-litre laboratory-scale reactor known as CAgSBio was designed and used. The operation of the reactor was based on the SBR system with a complete cycle operation of 3 hours and specifically designed to be operated for 24 hours continuously. Fresh activated sludge from local municipal wastewater treatment plants were used as inoculums (seed sludge) to start-up the reactor.

In addition, a 3-litre laboratory-scale reactor in Delft University of Technology (TU Delft), the Netherlands, operated at 20°C was used to compare the results on AGS granulation and performance. Furthermore, AGS developed at this low temperature as well as from a 1.4 m^3 pilot plant at Ede wastewater treatment plant, the Netherlands (fed with pre-treated domestic wastewater), were also used for AGS strength study to compare with AGS developed at 30°C. All analytical measurements performed in this study were conducted according to *Standard Methods for the Examination of Water and Wastewater* (APHA, 2005).

Two types of wastewater were used to develop AGS at 30°C i.e. synthetic wastewater and pre-treated domestic wastewater from local municipal wastewater treatment plants (actual wastewater). Finally, special attention on the study of settling behaviour and physical strength of AGS was also given in this thesis.

1.4 Importance of the Study

Since wastewater treatment systems are needed in dense populated regions, therefore, utilization of space is to be optimized. Available space for existing treatment plants is often limited, which can cause problems when treatment plants need to be extended for upgrading purposes. To avoid large footprints, compact treatment systems are needed. Since the last decade, different compact treatment systems have been developed, such as the biofilm system (Mulder *et al.*, 2001; Nicollela *et al.*, 2000), membrane bioreactors (Sourirajan, 1977; Ujang and Anderson, 1996; Ujang and Anderson, 2000; Ujang *et al.*, 2007) and AGS technology (Beun *et al.,* 2000; Tay *et al*., 2004; de Kreuk and van Loosdrecht, 2006; Zitomer *et al.,* 2007; Sunil *et al*., 2008). The importance of this study are as follows:-

i. This study provides technical input to develop a lab-scale compact domestic wastewater treatment system, known as CAgSBio, in which, it is specifically designed as a high, vertical and slender reactor.

ii. This study provides appropriate procedures on AGS granulation in hot climate conditions, especially at 30^{o}C.

iii. This study also provides insight on the performance of stable AGS to remove organic matter and nutrients simultaneously in a single unit reactor.

iv. This study also provides insight on the settling behaviour of AGS via comparing the settling profile study with other conventional sludge flocs and study on influence of both mechanical and aerated-mixing conditions to the AGS settling characteristics.

v. Through the results obtained from the settling behaviour study, a mixing criteria for AGS reactors was also developed.

vi. This study also provides procedures to evaluate the AGS strength based on the stability of AGS against shear stress. Determination of stability coefficient (S) was introduced as an indicator of AGS strength.

1.5 Organization of the Thesis

This thesis consists of six chapters. Chapter 1 gives a historical overview of domestic wastewater treatment and the need for more compact systems. An overview of the theoretical background of studies conducted on compact wastewater treatment system, especially AGS technology and theory of AGS granulation and performance were explained in Chapter 2. Chapter 3 presents a perspective and an outline of the study, materials and methods used as well as detailed procedures of each experiment conducted.

Chapters 4 and 5 present the results of the experimental studies that have been described in Chapter 3. Chapter 4 presents the results on AGS granulation and performance in hot climate conditions, especially at 30^{o}C, while Chapter 5 specially discussed on AGS settling behaviour and physical strength. The last chapter, Chapter 6, presents the conclusions of this study. Recommendations for future studies are also outlined in this chapter.

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<u>DEXTRAN BLUE TEST</u> (Beun *et al*., 2000)

Granules density determination by dextran blue

A known amount of a dextran blue solution (1 gL^{-1}) is added to a representative sample (and known amount) of the reactor, in a volume ratio of about 1 : 1. The mixture is gently mixed, and subsequently the granules are allowed to settle. A known amount of the liquid above the settled granules is removed and a sample is taken from it (fraction1). A known amount of demineralised waster is added to the granules. The mixture is mixed gently. The granules are allowed to settle. A known amount of the liquid above the settled granules is removed and a sample is taken from it (fraction 2). This last step is repeated until four fractions are obtained. The four fractions and the original dextran blue solution are analyzed by a spectrophotometer at 620 nm. Subsequently the volume of the biomass in the reactor sample could be calculated, since dextran blue only binds to the water and not to the biomass. Measuring also the dry weight of the reactor sample allows calculation of the granules (g biomass per L of granules).